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RESEARCH ARTICLE

40-Gbit/s 3-input all-optical priority encoder based on cross-gain modulation in two parallel semiconductor optical amplifiers

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Abstract A 3-input all-optical priority encoder is designed. Proof-of-concept experiment is performed at 40-Gbit/s based on a cross-gain modulation (XGM) in two parallel semiconductor optical amplifiers (SOAs). Output logic signals with over 10-dB extinction ratios (ERs) and clear open eye diagrams are obtained. No additional input light beam is used. The proposed scheme may be a promising candidate for future ultrafast all-optical digital signal processing circuits and computing systems.

Keywords optical computing, digital information processing, logic gates, cross-gain modulation (XGM), semiconductor optical amplifier (SOA)

1 Introduction

All-optical logic operations are expected to play important roles in future ultrafast all-optical networks and computing systems, where reducing latency and power consumption are of great interest [1]. In recent years, all-optical combinational logic circuits based on semiconductor optical amplifiers (SOAs) have been of great concern for their extensive applications, which are highly preferred as they can provide a more cost-efficient and flexible set of network functions. All-optical high-speed pseudo random bit sequence (PRBS) generation based on quantum-dot (QD)-SOA has been numerically analyzed [2]. We have demonstrated 40-Gbit/s simultaneous all-optical digital encoder and comparator in one module, based on the cross-gain modulation (XGM) and four wave mixing (FWM) in three parallel SOAs [3]. The priority encoder is a type of combinational logic circuit similar to a binary encoder, except that it generates an output code based on the input with the highest priority. Priority encoders are used extensively in digital and computer systems. For instance, microprocessor would interrupt its controllers given that the input with the highest priority is detected. However, to the best of our knowledge, there were few reports on the implementation of all-optical digital priority encoder.

In this paper, we propose and demonstrate a 3-input all-optical priority encoder at 40 Gbit/s exploiting the XGM in two parallel SOAs, without using any additional input light beams. The output logic signals exhibit impressive operating performance. This simple scheme may be a promising basic building block for future ultrafast all-optical signal processing circuits and computing systems.

2 Concept and principle

Digital encoder is a combinational logic circuit that generates a specific code at its outputs, such as binary or binary-coded decimal (BCD), in response to one or more active inputs. The standard binary encoder converts one of 2^n inputs into an n-bit output. However, one of the major disadvantages of a standard binary encoder is that it would produce an error at its outputs when there is more than one input present at logic level “1”. One simple way to overcome this problem is to “prioritize” the level of each input. If there is more than one input at logic level “1”, the actual output code will only correspond to the input with the highest priority, and all other inputs with a lower priority will be ignored. This type of digital encoder is known as a priority encoder.

Figure 1(a) shows the block diagram of a 3-input priority encoder, which consists of two output lines (Y_0 and Y_1), and three input lines (A, B, and C). The operation of the priority encoder can be described by the truth table shown in Fig. 1(b), where “X” means either “0” or “1”. Therefore, the combination containing two “X”s represents four

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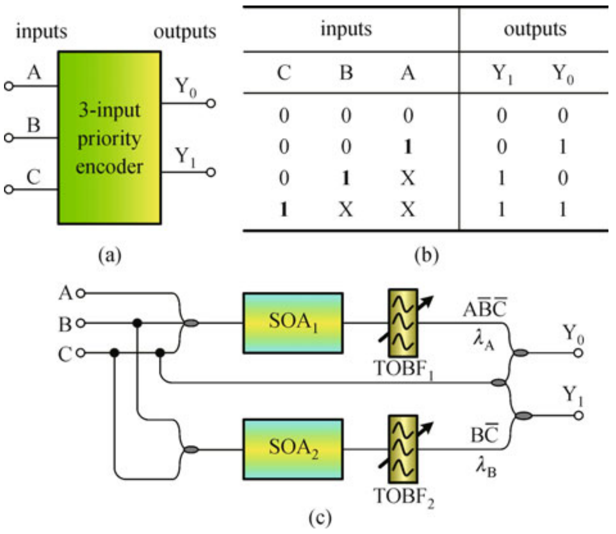

(a)

inputs			outputs	
C	B	A	Y_1	Y_0
0	0	0	0	0
0	0	**1**	0	1
0	**1**	X	1	0
1	X	X	1	1

(b)

(c)

Fig. 1 3-input digital priority encoder. (a) Block diagram; (b) logical truth table; (c) schematic diagram of 3-input all-optical digital priority encoder based on XGM in two parallel SOAs

binary combinations (0, 0), (0, 1), (1, 0), and (1, 1). We define the input data C has the highest priority, B has the next highest priority, and A has the lowest priority. The output Y_0 and Y_1 are “0” only when none of the inputs A, B, C are at logic level “1”. From the logical truth table, one can see that logic output $Y_0 = A\overline{B}\,\overline{C} + C$, $Y_1 = B\overline{C} + C$.

Figure 1(c) shows the schematic diagram of 3-input all-optical priority encoder using the XGM in two parallel SOAs. Three independent data signals A, B, and C with different wavelengths (λ_A, λ_B, and λ_C) are coupled and injected into SOA$_1$, where data B and C serve as pump beams, and data A as a probe. When the pump power is absent, the probe light will get high gain and be amplified in the SOA, and the output signal is high level. However, when the pump power is present, the probe will get less gain because of the gain saturation effect, and the output signal is low level. After SOA$_1$, logic $A\overline{B}\,\overline{C}$ can be extracted by a tunable bandpass filter (i.e., TOBF$_1$) centered on λ_A. Similarly, two input signals B, and C are coupled and injected into SOA$_2$, where C serves as a pump, and the data B as a probe. Logic $B\overline{C}$ can be extracted by TOBF$_2$ centered on λ_B. Thus, Y_0 can be derived by combining $A\overline{B}\,\overline{C}$ and C with a passive optical coupler, while Y_1 can be acquired by coupling $B\overline{C}$ and C with a passive optical coupler. Note that, in order to obtain high-quality output logic signals, logic $A\overline{B}\,\overline{C}$ and $B\overline{C}$ should be obtained by wavelength down-conversions [4], and the central wavelength of the used TOBFs should be detuned slightly to the probe wavelength to mitigate the pattern effect [5,6]. In this way, the logic functionalities of 3-input all-optical priority encoder is realized.

3 Experimental results and discussion

Experimental setup of 3-input priority encoder based on the XGM in two parallel SOAs is shown in Fig. 2. To facilitate description, the important measuring points and signal output locations, such as SO$_1$, SO$_2$, SO$_3$, and SO$_4$,

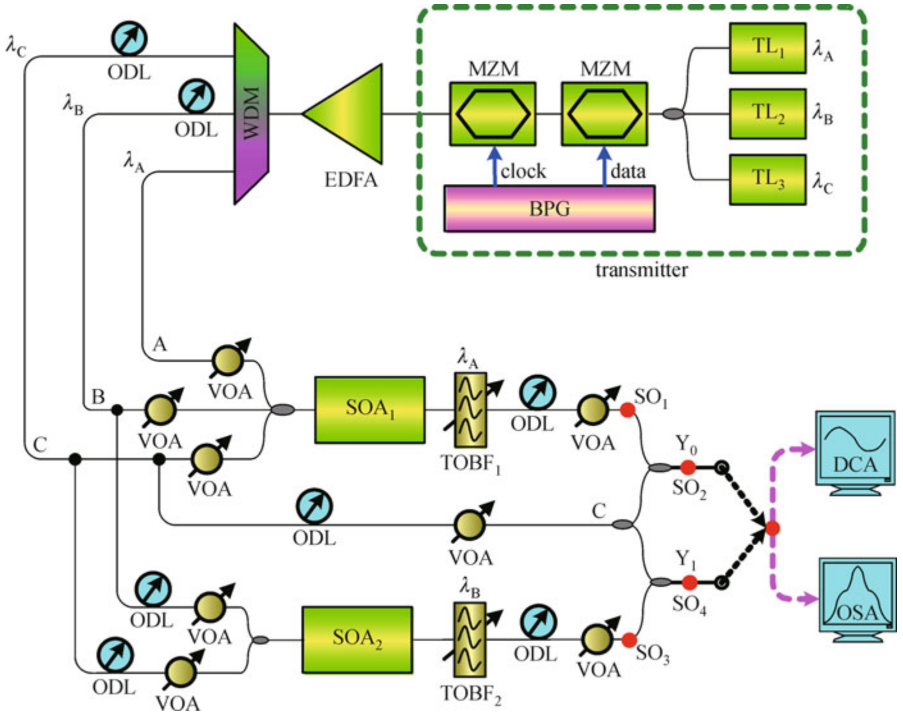

Fig. 2 Experimental setup of 3-input all-optical priority encoder based on XGM in two parallel SOAs

are marked in Fig. 2. Three continuous wave (CW) beams generate from three tunable lasers (TL, $\lambda_A = 1549.7$ nm, $\lambda_B = 1552.9$ nm, and $\lambda_C = 1556.1$ nm). The three CW beams are modulated simultaneously by two cascaded Mach-Zehnder modulators (MZMs), which generate 40-Gbit/s return-to-zero on-off keying (RZ-OOK) data streams with a 16 bit fixed data pattern provided by a bit pattern generator (BPG). The output modulated signals from MZMs are amplified by an erbium-doped fiber amplifier (EDFA), and de-multiplexed by a wavelength division demultiplexer (WDM) whose channel bandwidth and channel spacing are 1.0 and 1.6 nm, respectively. The separated signals are time-delayed differently from each other with optical delay lines (ODLs). Therefore, three data trains (i.e., A, B, and C) with different data patterns are derived. Their temporal traces are shown in Fig. 3.

In the experiment, the used SOAs (CIP, NL-SOA) with low polarization dependence (< 0.5 dB) are both biased at 240 mA, where the 10%–90% saturated gain recovery time is around 45 ps, and small signal regime gain at 1550 nm is about 30 dB. The powers of the input signals can be controlled by variable optical attenuators (VOAs) and EDFAs. Tunable Gaussian optical bandpass filters ($TOBF_1$ and $TOBF_2$) with 3 dB bandwidth of 0.4 nm are used to

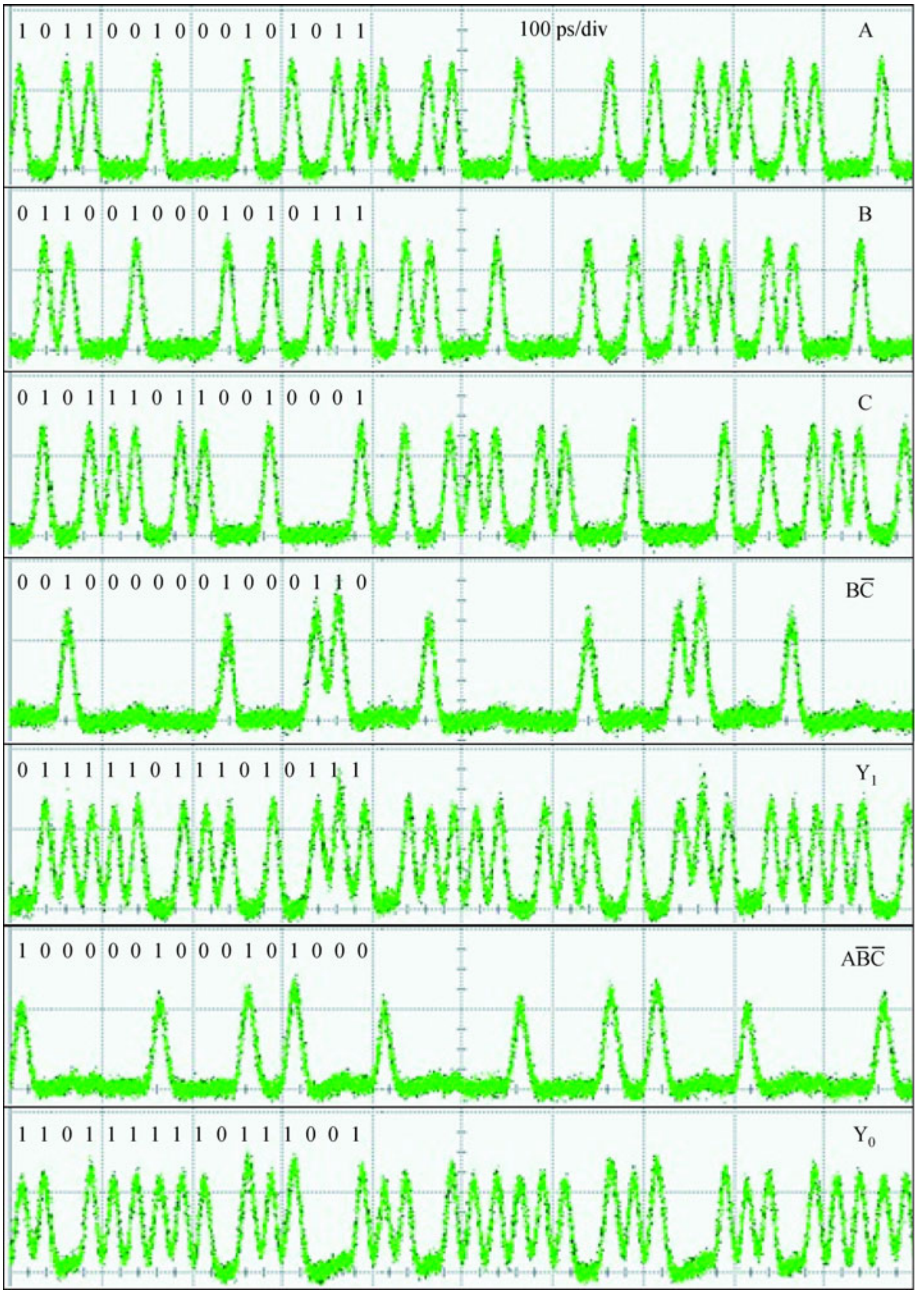

Fig. 3 Temporal traces of original signals (A, B, and C) and output logic signals (B$\overline{C}$, A$\overline{B}\overline{C}$, Y_0, and Y_1)

extract the converted signals after SOAs. Data A, B and C are coupled and injected into SOA_1. The measured average powers of data A, B and C are −4.62, 7.68 and 7.56 dBm at the input of the SOA_1, respectively. The converted signal $A\overline{B}\overline{C}$ is selected out by $TOBF_1$ centered at 1549.5 nm at the output location SO_1, due to the XGM in SOA_1. Finally, an optical spectrum analyzer (OSA, Anritsu MS9710C) and a digital communication analyzer (DCA, Agilent 86100C) are used to observe the optical spectra, temporal waveforms and eye diagrams of the output logic signals, respectively. Y_0 is then obtained at the output location SO_2, by combining $A\overline{B}\overline{C}$ and C with a 3 dB passive optical coupler. The temporal traces of output $A\overline{B}\overline{C}$ and Y_0 are illustrated in Fig. 3. The measured optical spectra of input and output SOA_1, and Y_0, are shown in Fig. 4(a). Similarly, data B and C are coupled and fed into SOA_2, the measured average powers of data B and C are −5.73 and 9.46 dBm at the input of the SOA_2, respectively. Due to the XGM in SOA_2, logic signal $B\overline{C}$ is extracted by $TOBF_2$ centered at 1552.7 nm, and observed at the output location SO_3 with the DCA and OSA. Y_1 is then derived at the output location SO_4 by coupling data streams $B\overline{C}$ and C using a 3 dB passive optical coupler. The temporal traces of $B\overline{C}$ and Y_1 are shown in Fig. 3. The measured optical spectra of input and output SOA_2, as well as Y_1, are illustrated in Fig. 4(b). It should be worth noting that the coupling powers of signals $A\overline{B}\overline{C}$ and C, $B\overline{C}$ and C must be identity before 3 dB passive optical coupler, by adjusting the VOAs.

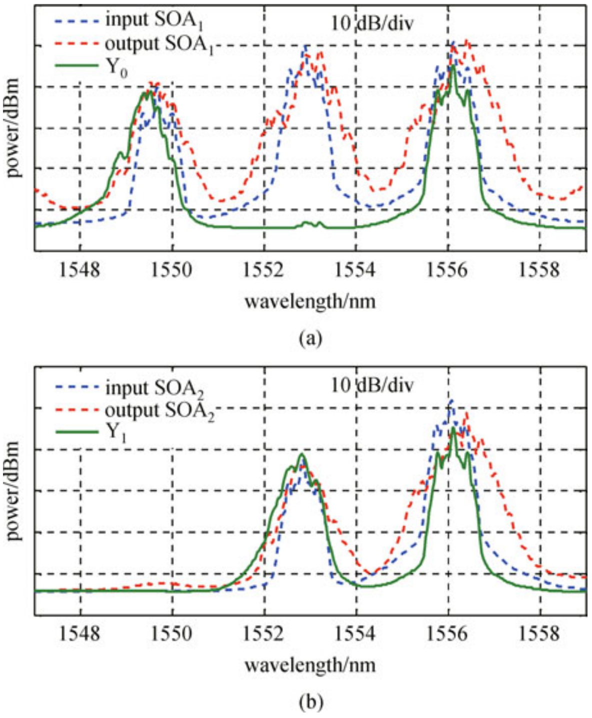

Fig. 4 Measured optical spectra of (a) input SOA_1, output SOA_1, and Y_0; (b) input SOA_2, output SOA_2, and Y_1

In order to evaluate the operating performance of various logic gates, the extinction ratios (ERs) and eye opening factors (EOFs) have been measured using 2^{23}–1 PRBS instead of the 16 bit fixed pattern mentioned above. ERs and EOFs of the output signals $B\overline{C}$, $A\overline{B}\overline{C}$, Y_0, and Y_1 are shown in Fig. 5. The insets are the measured eye diagrams of the best and the worst cases. It should be noted that the thick bottom rail of Y_0 is caused by the ghost pulses generated by the XGM process, and the thick upper eyelid is mainly derived from the pattern effect in the XGM process. In addition, the thick upper eyelid is partially caused by the broadened widths of the output pulses, because the 3-dB bandwidth of the used TOBFs is only 0.4 nm.

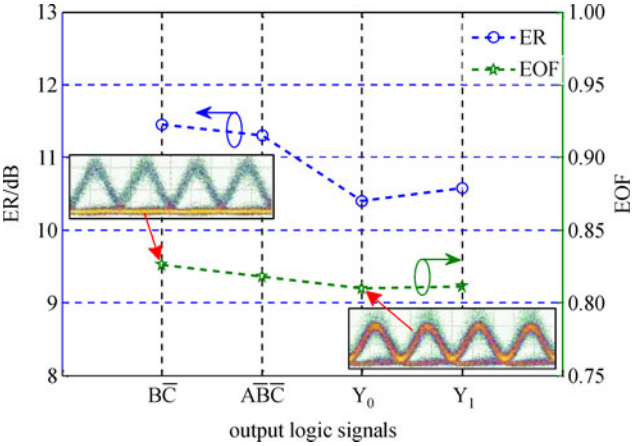

Fig. 5 Measured ERs (left) and EOFs (right) of output logic signals ($B\overline{C}$, $A\overline{B}\overline{C}$, Y_0, and Y_1) at 2^{23}–1 PRBS. Insets: eye diagrams at the cases indicated

In the experiment, three key issues on which impact on the quality of output logic signals, should be addressed. Firstly, there is an optimum power match between input pump and probe light beam, and non-optimum power difference may lead to the operating performance degradation. The optimum power difference of the two incoming signals at the input of the SOA is about 12–14 dB, as confirmed in Fig. 4. Secondly, in order to mitigate the pattern effect owing to the slow carriers recovery time of SOAs and increase the operating speed, the central wavelength of the used TOBF is tuned to the blue side of the probe wavelength (around 0.2 nm), where the total insertion loss of the blue-shifted TOBFs are around 7 dB. In addition, added noises of the output signals Y_0 and Y_1 are derived by coupling the two different data trains with different wavelengths. Therefore, the most of the degradation of output logic signals comes from the residual power in case that the pump and probe powers are both present, the pattern effect, added noise, as well as the effect of the amplified spontaneous emission (ASE) noise of the SOAs.

In general, a priority encoder of a larger number of input lines could be developed and implemented by several data selectors of a smaller number of inputs. Of course, there will be a certain degree of degradation of output logic signals, with the inputs increasing. Thereby, the scheme is capable of expanding to large-scale priority encoder array and is a potential basic building block for future ultrafast all-optical networks and computing systems.

4 Conclusions

A design of 3-input all-optical digital priority encoder has been proposed. Proof-of-concept experiment is carried out at 40-Gbit/s based on the XGM in two parallel SOAs. The output results with over 10 dB ERs and clear open eye diagrams are derived without using any additional input light beams. The proposed scheme may be a potential candidate for future ultrafast all-optical signal processing circuits and computing systems.

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